



INSTRUMENT AND SPACECRAFT DESIGN

**Artist's
concept of
two SIM
instrument
architecture
design varia-
tions being
considered
by the
Project.**

The SIM instrument is an optical long-baseline Michelson stellar interferometer, consisting of optics, actuators, sensors, and computers for acquisition and tracking of the stellar fringe pattern. In SIM's architecture, based on the Orbiting Stellar Interferometer concept, three interferometers are operated simultaneously. While one interferometer is taking science data, two guide interferometers are used to determine the orientation of the baseline of the science interferometer.

Two design variations of the instrument are under study, both of which are capable of meeting all science requirements. Most of the instrument subsystems are common to the two design variations, such as the delay lines, astrometric beam combiner, nulling beam combiner, and laser metrology system.

The performance of the instrument is designed to a wide-angle, 5-year-mission accuracy of 4 microarcseconds down to a limiting visual magnitude of 20. Additionally, SIM will demonstrate starlight nulling to 1 part in 10,000. These design goals require tight control of the various error sources.

The spacecraft carries the instrument components and provides essential operational functions including power,

attitude control, propulsion, communication and thermal control. The spacecraft and the instrument together form the flight system.

Instrument Design

The instrument consists of three simultaneously operated optical Michelson stellar interferometers. The science interferometer baseline is 10 meters. At any time, one interferometer takes science data while the other two act as guide interferometers to determine the orientation of the science baseline in three-dimensional space.

The two design variations of this architecture currently under study by the SIM Project are "Son of Sim" and "Sim Classic." The Son of SIM design uses a com-

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beam com-
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nulling
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will be part
of SIM.**

mon baseline for the three guide and science interferometers and a hexapod pointing system for acquisition of targets. The SIM Classic design has three separate interferometer baselines and an external metrology truss to monitor the relative positions of the three baselines. In this design, targets are acquired using siderostats. The SIM Project will make a final selection between these two designs in 1999. Technology readiness, science performance, mission risk, cost, and schedule impact are the criteria that will be used as discriminators in the decision.

The fundamental design of a single interferometer is the same in each of the two designs — the pointing subsystem acquires the starlight in each arm of the interferometer and sends it to the delay lines and the beam combiners. The pointing subsystem has a coarse and a fine actuator. The coarse actuator acquires stars over a 15-degree field of regard without reorienting the spacecraft; the fine actuator provides high-precision pointing control required for high-visibility stellar fringes. A coarse pointing sensor is also located in the pointing system. In addition, the pointing subsystem compresses the stellar beam from a 33-centimeter, collection-aperture diameter to a 4.5-centimeter-diameter beam. This compression enables the use of

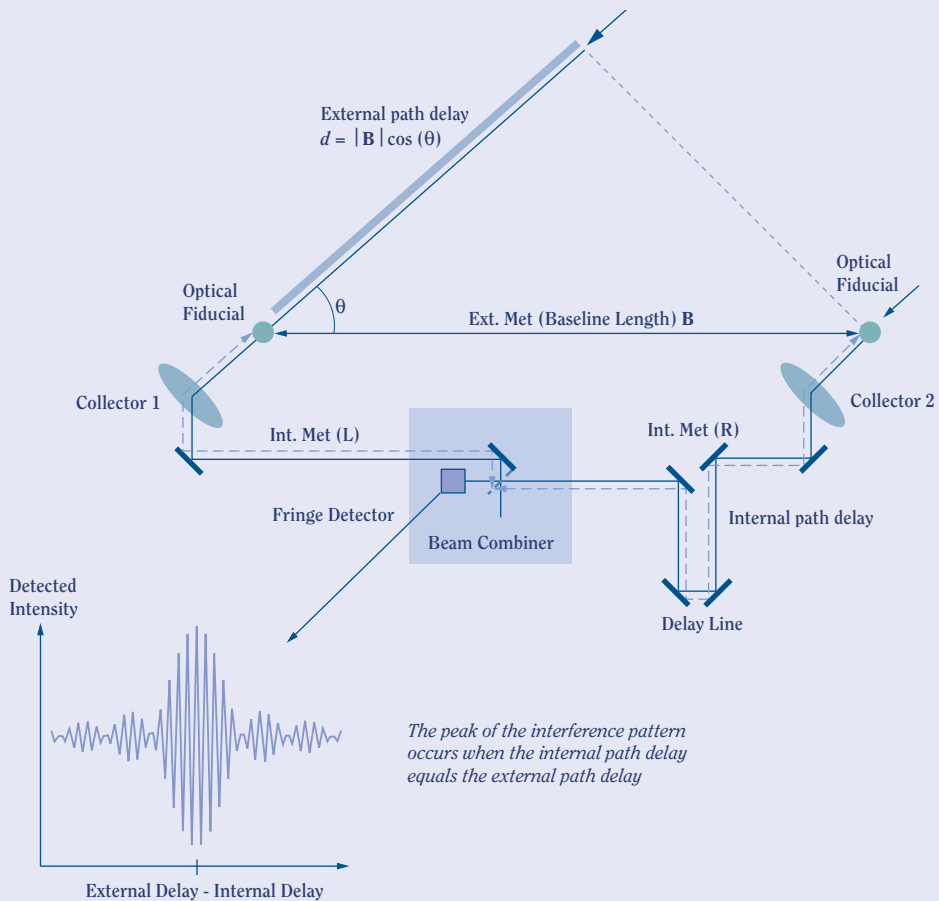
smaller optics in the remainder of the beam train.

From the pointing subsystem, the starlight goes to the delay lines, which modulate the pathlength difference between the two interferometer arms. Like the pointing subsystem, the delay lines have coarse and fine actuators. The coarse stage moves by several meters as necessary to acquire fringes for stars within a 15-degree field of regard. The fine actuator provides high-bandwidth pathlength modulation to control the optical path difference precisely and reject jitter from onboard disturbance sources.

From the delay line, the starlight is transferred to the beam combiner, and the position of the resulting white-light fringe is recorded on a detector. The fringe position is then used as both the science data and as a sensor signal for the delay-line actuator. The beam combiner also contains a detector to measure the tilt of the incoming wavefronts. This sensor controls the fast-steering mirror in the pointing subsystem. In addition to these astrometric beam combiners, a nulling combiner will be part of the SIM instrument and will be switched in for nulling demonstrations.

PRINCIPLE OF A SINGLE ASTROMETRIC INTERFEROMETER

A single interferometer consists of two collectors, each located at one end of the baseline; a delay line; and a beam combiner. Starlight is sent from the collector toward the beam combiner to form a white-light fringe. Because starlight is white, fringes occur only when the optical pathlength from the star through the left interferometer arm — all the way to the combination point in the beam combiner — is equal to the optical path traversed through the right interferometer arm. To make this equalization possible, an optical delay line is added to one arm of the interferometer to adjust the optical path of that arm.



Once the delay line is set to a position where the paths are exactly equal, the angle to the star can be determined by measuring optical pathlengths in the interferometer. The interferometer baseline **B** is the vector formed by the vertices of the two fiducials located in front or at the location of the first collector optics. Because the starlight wavefront will typically not be parallel to the optical baseline, the optical path from the star to the left fiducial will be different than the optical path to the right fiducial by an amount d . The angle between the baseline vector and the star is given simply by $\cos^{-1}(d/|B|)$, where $|B|$ is the length of the baseline vector. The distances d and $|B|$ are measured by the metrology gauges. The length of the baseline is measured by an external metrology gauge running between the left and right fiducials. The distance d is determined by measuring the starlight path from the fiducials in each arm to the beam combination point.

The metrology subsystem consists of optical fiducials located in front of the first pointing optic that define the interferometer baseline, external metrology measuring the length of the interferometer baseline (and relative baseline orientation in SIM Classic), and internal metrology measuring the optical path from the beam combiner to the optical fiducial. Heterodyne metrology gauges are used to monitor the distance between the optical fiducials. A separate internal metrology gauge is used for each arm of the interferometer, and is injected into the center of the starlight beam inside the beam combiner. This metrology beam will measure the path from a fiducial inside the combiner to the baseline fiducials.

Son of SIM

In the Son of SIM design, the three guide and science interferometers use a common baseline defined by the vertex of metrology fiducials. The length of the baseline is measured using an external metrology laser gauge. In order to acquire targets within the 15-degree field of regard while keeping the fiducials centered in the starlight beam, the beam compressors in the pointing subsystem must both translate and tilt. This is accomplished by mounting the beam compressors on hexapods, allowing 6-degrees-of-freedom control. Four beam compressors are co-located in a single collector pod at each end of the baseline; the fourth compressor is a redundant unit. From the collector pods, light is sent to the delay lines and the

beam combiners. In order to make measurements at different baseline lengths, each of the collector pods can be translated on rails toward the combiner unit.

The Son of SIM pointing system consists of a two-stage hexapod, beam compressor, relay optics, coarse acquisition camera, and a translation camera. Most of the hardware is located on an optical bench actuated by the hexapod. The exception is the alignment mirror directing the starlight beam from the hexapod to the rest of the optical train. The hexapod points over a 15-degree range with a pointing accuracy of 0.1 arcsecond. The hexapod will also translate the compressor by about ± 7 centimeters, with a resolution of 8 micrometers, to keep the corner cube in the center of the starlight beam. Two stages are required to cover the large dynamic range in pointing and translation. The fine stage uses PZT (lead zirconate titanate) actuators with a 10-micrometer stroke and a resolution of 0.2 nanometer. Capacitive sensors integrated into the PZT are used to encode the position of the fine actuator. The coarse stage uses a motor-driven ball screw with 1-micrometer resolution and high-precision encoders. A pair of bearing flexures supports each end of each strut.

A coarse-acquisition camera and a translation sensor are used to sense the posi-

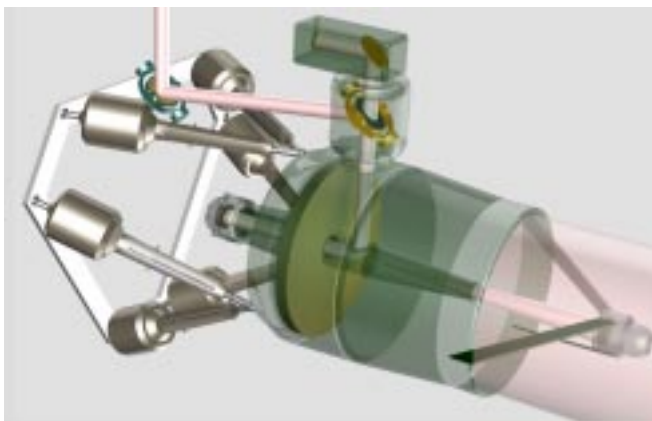
tion of the collector optical bench in pointing and positioning. A fiber is inserted into the optical fiducial to illuminate the translation sensor. The coarse-acquisition camera will use a low-noise CCD camera for high sensitivity.

Starlight is captured by a 33-centimeter beam compressor and reduced to a 4.5-centimeter beam. The light is then incident on the fast-steering mirror (FSM), which provides high-bandwidth and high-resolution pointing control for the system. The FSM will use PZT



SON OF SIM

Artist's concept of the Son of SIM design.



COLLECTOR ASSEMBLY

The hexapod collector assembly allows 6-degrees-of-freedom control.

actuators and will be momentum compensated so as not to introduce disturbances to the structure. The FSM will have a resolution of better than 70 milliarcseconds and will operate at up to 1 kilohertz. Starlight then propagates to the alignment mirror, which moves to compensate for the position of the hexapod and to direct the beam into the remainder of the optical train with a minimum of tilt and translation. The alignment mirror will have a range of 7.5 degrees and a resolution of 1 arcsecond, and will operate at a bandwidth of a few hertz.

SIM Classic

In the SIM Classic design, the three guide and science interferometers use three separate baselines, and an external metrology truss measures the relative

orientations of the baselines. Having three separate baselines simplifies the pointing system, and a siderostat — similar to those used on ground-based interferometers — can be used. In SIM Classic, the pointing subsystem consists of seven siderostat bays distributed along the spacecraft structure. At any one time, six bays are used and the seventh provides redundancy. Starlight from the siderostat bays is directed to an optics boom that houses the delay lines and beam combiners. A switchyard transfers light from any siderostat bay into any delay line, allowing measurements to be made at a number of different baselines.

Each siderostat bay holds a siderostat, an off-axis 7.5:1 beam compressor, FSM, and coarse-acquisition camera. The siderostat holds a 40-centimeter flat mirror pointed 30 degrees from the optical axis of the beam compressor. The siderostat uses two-axis flexures and voice coils to move the mirror over a 7.5-degree range. The siderostat actuator has high-precision rotary encoders with a resolution of 20 milliarcseconds. In addition, the siderostat can articulate so that it is facing normal to the beam compressor, thus reflecting an optical calibration signal back into the optical train. A corner cube at the center of the back side of each siderostat serves as the end point of the interferometer baseline. The corner cube is optically contacted to



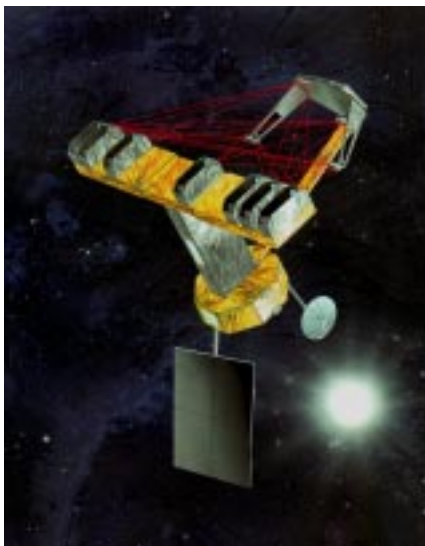
IM will operate three interferometers simultaneously at any given time. While one interferometer is taking science data, two additional guide interferometers are used to determine the orientation of the science interferometer baseline. The guide interferometers observe a pair of bright stars while the science interferometer sequentially observes a number of science targets. The interferometric measurements, fringe, and metrology measurements on the guide stars are used to determine the attitude of the baseline in inertial space.

Knowledge of the absolute attitude is actually not essential. What is important is that the changes in the baseline orientation during the observation period (~1 hour) are known accurately. The initial orientation of the baseline is solved in the postprocessing of the astrometric data.

Observing dim science targets is a major challenge for the SIM instrument. Acquisition and measurements of white-light fringes will be limited by the changes in the attitude of the spacecraft and from onboard disturbances. The instrument will stabilize the position of the science fringe by using the two guide interferometers and the internal metrology system. The two guide interferometers, locked on bright stars, will sense the attitude of the spacecraft at high bandwidth, while the internal metrology system monitors the optical-path vibrations along the optical train. By using information from these sources, the delay line on the science interferometer can be commanded to stabilize the optical path of the science star, enabling long integration times on the target. This technique is called pathlength feed-forward.

SIM CLASSIC

Artist's concept of the SIM Classic design.



the siderostat surface such that the vertex is coaligned with the mirror surface and the two siderostat axes. It is critical that the three interferometer baselines are co-parallel. This is due to the fact that the two guide interferometers provide attitude information in two of the three angular directions. The third dimension is the roll about the baseline vector. Sensing of this direction is significantly relaxed if the interferometer baselines are parallel to one another. Translation actuators underneath each siderostat mirror are used to align the three baselines after the initial instru-

ment deployment to within 10 micrometers of being parallel. The external metrology will monitor the misalignment between the three baselines; it is expected that this alignment will have to be done only every few months. Starlight exiting the beam compressor is sent to an FSM, providing the high frequency pointing control of the starlight. From there, starlight proceeds to a turning mirror, injecting the starlight into the remainder of the optical train.

The external metrology truss measures the lengths and relative orientations of the three interferometer baselines. A tetrahedron with a 3.5-meter base and a 1.0-meter height, located 6 meters from the siderostat boom, is deployed after launch and is used to triangulate on the position of each of the seven siderostat fiducials. Only three vertices of the tetrahedron are required to perform the triangulation; the fourth vertex is for redundancy. An external metrology beam-launcher assembly is located at each vertex of the tetrahedron. Each beam-launcher assembly consists of seven beam launchers and a multiple corner cube fiducial in a temperature-stable enclosure. In addition to the 28 beams between the siderostats and the tetrahedron vertices, six additional beams are used to measure the distances between the fiducials in the tetrahedron.

Delay Lines

The delay line subsystem changes the optical pathlength between the two arms of the interferometer. The delay line uses a cat's-eye optical configuration and has three levels of actuation. A coarse stage, consisting of a band drive and stepper motor, moves the entire cat's-eye assembly over a range of 2 meters. A voice-coil stage moves the cat's-eye assembly over a 1-centimeter range at low frequencies (<10 hertz), and a PZT stage located at the secondary of the cat's eye provides the high-bandwidth actuation (10–1,000 hertz) with a stroke of a few micrometers. During normal observations, the delay-line coarse stage will be locked down and only the voice-coil and PZT stages will be used for pathlength control. Both those stages will be momentum compensated to minimize disturbances induced by the delay line to the rest of the instrument.

Astrometric Beam Combiner

The last element in the light path is the astrometric beam combiner. At this point, the pathlength difference for light from the two arms of the interferometer has been compensated by the delay lines, and a white-light fringe can form as soon as light from the two arms is combined. The camera in the beam-

combiner system can now record this fringe pattern. A single camera with two separate detectors is used for the tilt and fringe detection.

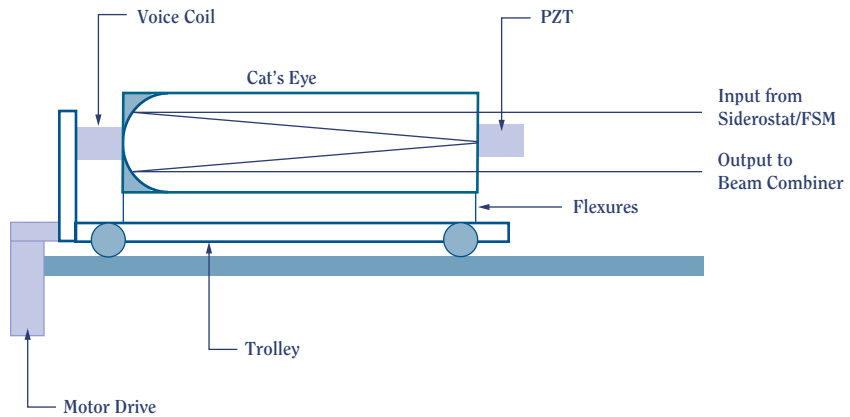
In addition to collecting the science data, the beam combiner generates the control signals for the delay lines and the pointing subsystem. For this purpose, the starlight pupil plane is divided into three regions. The inside region is used to propagate the internal metrology beam from the combiner to the optical fiducials. Light from the middle annulus is combined to form the stellar fringe — the science data. Light from an outside annulus is used to determine the wavefront tilt.

The stellar fringe is spectrally dispersed using a prism to obtain pathlength and visibility information at different wavelengths. There are two techniques to determine the exact position of the fringe. In the dispersed-fringe technique, the number of cycles in the spectrometer output measures the optical pathlength difference. A large number of cycles indicates a large deviation from zero. In the modulated-fringe technique, the delay lines are set to the zero-pathlength position and quarter (or eighth) wave steps are introduced into the optical

**External
metrology
monitors
changes
in the
lengths and
orientations
of the
baselines.**

DELAY LINE

*Schematic of
an optical delay
line.*



path. Measurements of the intensity pattern at different steps are used to compute the phase of the fringe position.

Nulling Beam Combiner

Light from a planet in orbit around a distant star can only be detected if the much brighter starlight can be suppressed many orders of magnitudes while the instrument remains sensitive to the signal from the planet. One approach to achieving this goal is to employ a nulling interferometer. Here, a phase difference of 180 degrees is added to the delay to cancel the light at the position of the star through destructive interference. The challenge is to introduce this phase shift independent of the starlight wavelength.

SIM will demonstrate the technique of a nulling interferometer to a depth of 1 part in 10,000 at optical wavelengths. This objective calls for the addition of a nulling beam combiner producing a broadband achromatic null. Two validation studies are currently under way. In the JPL-developed study, an achromatic 180-degree phase flip is introduced between the combining beams by rotationally shearing one of the interferometer beams. In the second study, a wavelength-independent path delay is introduced through a dichroic waveplate. In order to achieve the required null depth, both combiner designs will have to be able to match the intensity and polarization from each interferometer arm. The required levels of control of the optical pathlength and pointing are more stringent than those required

for astrometry. Additionally, minimization of surface errors and polarization effects, and equalized surface throughput, are essential.

Metrology Subsystem

The metrology subsystem measures distances in the interferometer critical to the high-precision angular measurements. The metrology subsystem utilizes heterodyne metrology laser gauges similar to commercial systems to measure the interferometer baseline length and the internal optical pathlengths. The science requirements translate directly to a requirement on the accuracy of the metrology gauges. The metrology gauges will have to measure relative changes with an accuracy of 20 picometers.

The metrology subsystem is subdivided into the metrology fiducials, the beam launcher, and the metrology sources. The fiducials serve as the endpoints of the measurement system. The beam launchers inject laser light to measure the distance between the fiducials. Finally, the metrology source generates the optical signal and frequency offsets necessary to derive the metrology signal.

The metrology subsystem uses double-faced corner cubes as the optical fiducials for both the external and internal metrology gauges. One face of the corner cube is used by the external metrology gauge to measure the baseline

DETECTOR CHARACTERISTICS

Type	CCD — backside illuminated
Quantum efficiency	0.7
CCD read noise	3 e ⁻

ANGLE TRACKER

Detector size	80 × 80
Angle tracker	Two 4 × 4 pixel areas
Maximum readout rate	1,000 areas/s

FRINGE TRACKER

Detector size	80 × 80
Spectrometer band	0.4 – 0.9 μm
Spectrometer channels	1,4, 8, 16, or 80
Maximum readout rate	1,000 spectra/s
Maximum integration time	1 min

length. The other face of the same corner cube is used as a common endpoint for all four internal metrology gauges. It is critical that the vertices between the different corner cubes are coaligned in order to minimize the offset between the external metrology measurement and the internal metrology measurement.

The metrology gauge beam launchers use two different laser polarizations, which have been frequency shifted with

COMBINER CAMERA

Characteristics of astrometric beam-combiner camera elements.

respect to each other. Through the use of polarizing beamsplitters and quarter-wave plates, the s-polarization performs a round trip to each of the optical fiducials before reaching the “unknown” detector. The p-polarization goes straight through to the detector. The interference of the two beams will produce an electrical signal at the frequency shift between the two input beams. The phase of this signal is then a function of the distance the s-polarization has traveled. By measuring this phase, one can monitor the changes in distance between the

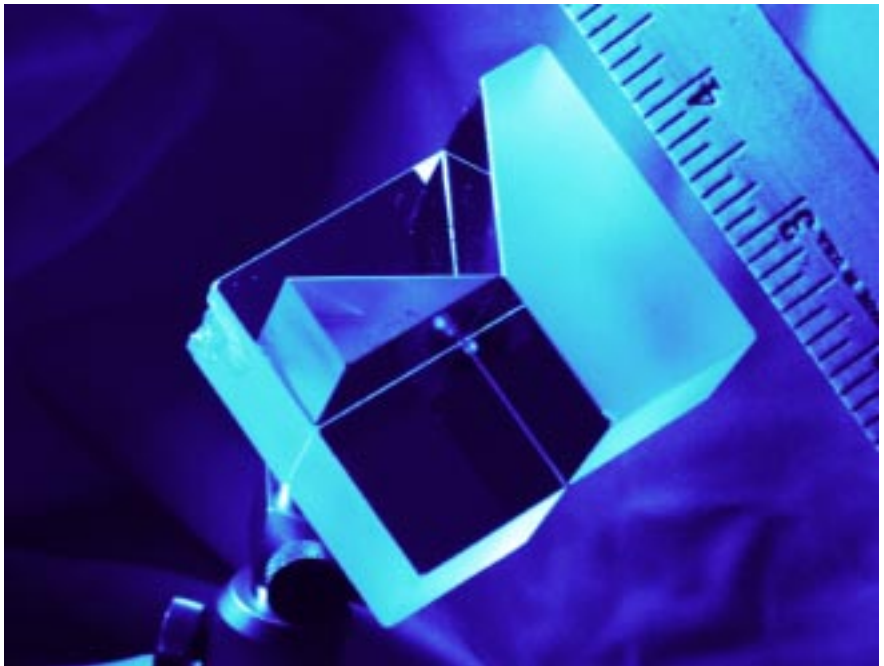
two fiducials. An additional “reference” detector is used prior to launching the metrology beam to calibrate the optical path differences between the two fibers used to distribute the s- and p-polarized beams.

All metrology gauges use laser light from a common metrology source. Infrared light was chosen in order to eliminate contamination of the starlight signal by the metrology. Acousto-optic frequency shifters and modulators are used to create the frequency offsets necessary to

CORNER CUBE FIDUCIAL

Corner cube fiducial prototype.

The vertices are coaligned to less than $1\ \mu\text{m}$, adequate to meet the SIM requirements.



produce the heterodyne metrology signal. The metrology gauge will be able to track velocities up to 1 centimeter per second. Polarization-maintaining fibers are used to distribute light to the various beam launchers.

Instrument Software and Electronics

The instrument flight software implements the set of in-flight, real-time command, data, and control functions required to operate the SIM flight instrument. Instrument command and data functions include startup, instrument sequence decoding and execution, storage of science and engineering data, and packaging for telemetry downlink. In addition to normal instrument operations, the flight software will provide the functionality for ground testability and fault protection, enabling autonomous operation without ground-assisted reconfiguration.

The control functions enable the instrument to track on a stellar fringe and monitor the critical instrument parameters through the metrology system. The control system includes alignment, pointing control, and pathlength control. Alignment control establishes and maintains the instrument beam geometry. Alignment is typically executed after the initial instrument deployment

and after a major instrument configuration change (e.g., moving collector pods). The pointing-control system includes coarse pointing and fine pointing. Coarse-pointing acquisition and control actuates hexapod or siderostat motion to position and hold a target star image on the collector coarse-pointing camera focal plane. Fine-pointing acquisition utilizes the fast-steering mirror control to position and hold the target star image location on the beam combiner focal plane. In addition, angle feed-forward control algorithms are used to point the instrument on a dim science star using information from nearby bright reference stars. The pathlength control system involves control of the delay line in order to form a stellar fringe pattern on the beam combiner. Information from the internal and external metrology and the beam combiner is used to control the delay line in order to acquire a fringe and to keep the pathlengths equal through each of the interferometer arms. In the case of dim science targets, a pathlength feed-forward control algorithm utilizes information from the guide interferometers and the attitude control system to estimate the correct position for the science delay line.

The control functions enable the instrument to track on a stellar fringe and monitor the critical instrument parameters through the metrology system.

**METROLOGY
SOURCE**

*Specifications
for the SIM
metrology
subsystem.*

The SIM instrument software architecture is derived from the Palomar Testbed Interferometer and Keck Interferometer designs. The software is written in C++ for a VME-based real-time operating system. The software allows the use of multiple computers to control the interferometer and enables flexibility in the design of the flight instrument electronics and hardware.

The onboard instrument electronics provide the real-time processors, data busses, and component interface electronics necessary to control the SIM instrument. A total estimated processing throughput of several hundred MIPS is required on board to support command and telemetry streams concurrently with closure of the high-rate pointing, me-

trology, and optical pathlength difference control loops in science operational modes. A multiprocessor architecture supports partitioning of software functionality across processors and micro-controllers for flexibility in subsystem partitioning, software development, and flight system implementation, integration, and test. Data bus latency requirements are driven by the closure of three concurrent sets of phasing control loops with sampling rates in the kilohertz and the associated estimators, pointing control, and related functions. Single fault-tolerance capability also drives the maximum allowable latencies across the instrument data bus.

Instrument Performance

SIM has three critical performance challenges — sensitivity, wide-angle and narrow-angle astrometry, and nulling.

Sensitivity reflects the ability of the SIM instrument to acquire and measure fringe positions — the critical science data. To accomplish this, high levels of pathlength and pointing control are necessary. Astrometric performance reflects the ability of the SIM instrument to make its measurements at levels consistent with the scientific objectives of the mission. The astrometric performance will be limited by errors in the sensor systems (metrology and fringe tracker)

COMPONENT	SPECIFICATIONS
Laser	Lightwave Nd:YAG laser
Laser wavelength	1.319 μm
Laser power	200 mW
Frequency shifter/modulator	Acousto-optic cell
Shift frequency	100 kHz
Frequency modulator	80 MHz
Modulation rate	1,000 Hz
Frequency stabilization	1 part in 10^9

SENSITIVITY

The (angular) astrometric rms sensitivity of the SIM instrument is given by $\sigma = \frac{\lambda}{2\pi B V \sqrt{N}}$ where λ is the observation wavelength, B is the baseline length, V is the system visibility, and N is the number of detected photons. The number of detected photons N , in turn, depends on the collecting area, system throughput, and detector quantum efficiency. SIM is expected to have a system throughput of 0.6 and a system visibility of 0.7, and will use detectors with an average quantum efficiency of 0.7. With 33-centimeter collecting apertures and half the photons going to the pointing sensor, the expected integration time required to make a 7.5-microarcsecond measurement on objects of varying visual magnitudes is shown in the accompanying table.

INTEGRATION TIMES, 7.5-MICROARCSECOND MEASUREMENT

VISUAL MAGNITUDE	INTEGRATION TIME (s)
6	0.04
8	0.2
10	1.6
12	10.4
14	65.6
16	414
18	2,600
20	16,500

SENSITIVITY*(opposite)**Factors contributing to SIM's instrument sensitivity.*

and systematic errors in the instrument. Finally, nulling performance reflects the ability of the instrument to perform the null experiment at the 10^{-4} level.

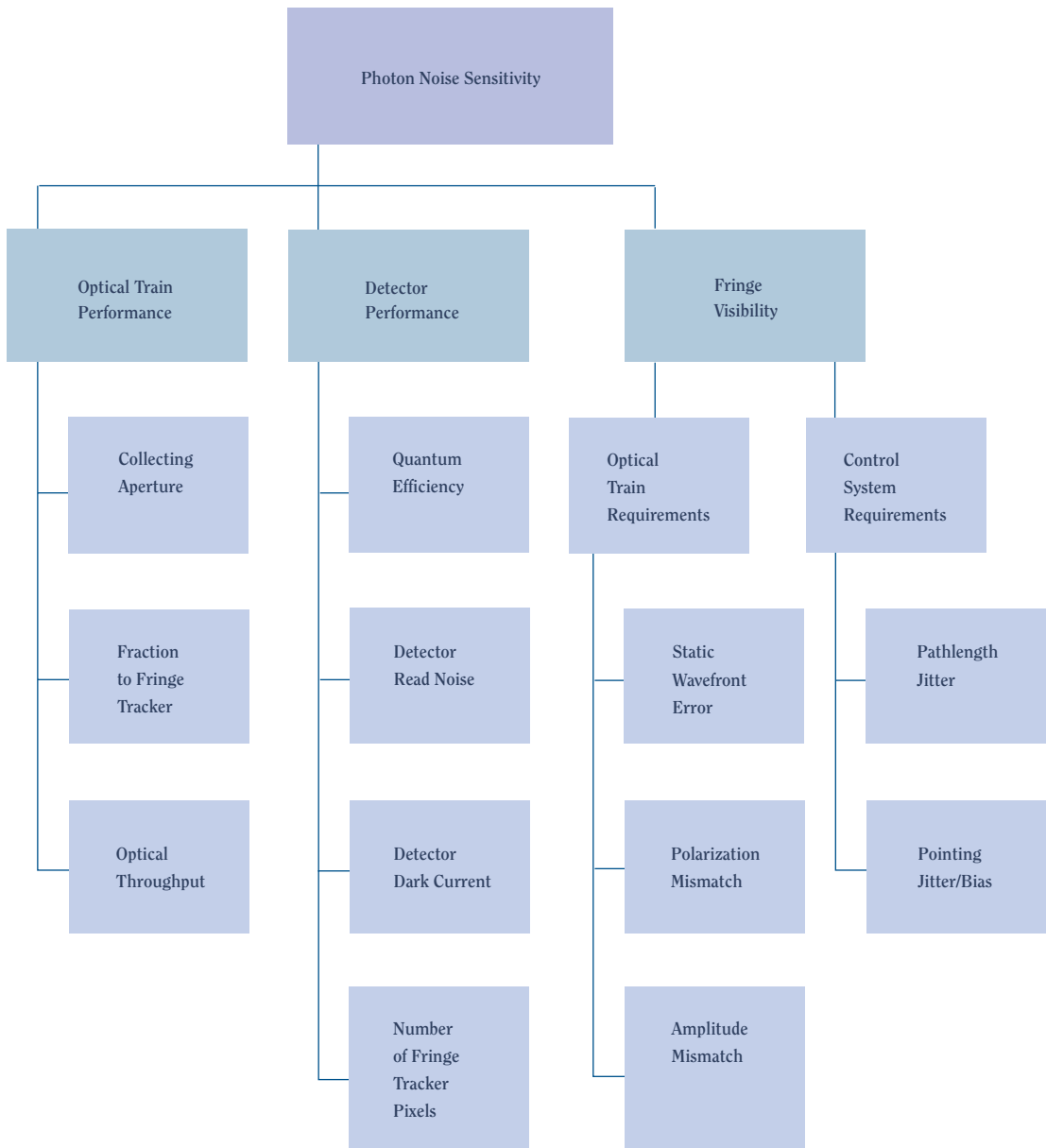
Sensitivity. A critical parameter in the operation of the SIM instrument is the system visibility. This parameter affects not only the instrument throughput, but if the visibility becomes too low, acquisition and tracking of stellar fringes is no longer possible. The major contributor to a decrease in system visibility is the static wavefront error in the interferometer optical train. By using $\lambda/20$ peak-to-valley optics, the visibility reduction can be kept below 20 percent. It is the pointing and pathlength control residual requirements that provide the design challenge. To meet sensitivity requirements, each interferometer arm must be pointed to better than 30 milliarcseconds and the difference in optical path between the two arms must be less than 10 nanometers. These two control systems will have to operate in the presence of disturbances in the spacecraft. Disturbances can arise from a number of sources, including reaction-wheel-induced disturbances, instrument-induced jitter, and microdynamic events arising from thermal stresses that build up in the structure.

Astrometry. Simulations have shown that for a 4-microarcsecond, wide-angle accu-

racy over 5 years, the instrument will need to make single astrometric measurements with an error of less than 7.5 microarcseconds. This angle translates directly into an error in the baseline knowledge and the pathlength control. Astrometric accuracy is affected by key error sources in the instrument — metrology errors, fringe-measurement errors, thermal errors, “beam-walk” errors, and stellar-aberration errors.

Metrology errors arise from imperfections in the gauges measuring the critical positions of the interferometer components. Errors show up in both the external and internal metrology measurements. Sources include thermal effects in the gauges, errors in the detection and electronic system, mispointing of the laser beams in the metrology gauges, and aberrations in the optical fiducials. Each of these sources causes a difference between the output of the metrology system and the ideal geometrical distance between the vertices of the corner cubes. It is important to note that these errors are not errors in the absolute distances but rather in the changes in distances as the interferometer observes different stars.

Fringe-measurement errors occur in the detection and measurement of the white-light fringes due to systematic er-



ASTROMETRIC ACCURACY

(opposite)

Sources contributing to SIM's wide-angle astrometric error.

rors. Limitations due to photon noise are captured in the photon noise sensitivity chart. Sources include imperfections in the detector quantum efficiency and responsivity, miscalibration of the spectrometer, and quantization errors in the fringe dithering algorithm.

Thermal errors are caused by a change in the thermal environment that causes a warpage of the mirror surface. The internal metrology beam provides only a subaperture measurement of the optical path at the center of the starlight pupil. Variations in the optical path outside the interrogation region are not sensed. This causes stringent thermal requirements on the optical components of the instrument. As an example, a 2.6-millikelvin change in the front-to-back temperature difference of the compressor primary over a 1-hour period will cause a 40-picometer error in the astrometric measurement. The SIM Project is currently investigating alternatives to the subaperture internal metrology gauge that will allow wavefront sensing over the entire aperture. These full-aperture metrology schemes all involve the use of a holographic optical element on the compressor primary, creating a full-size metrology beam parallel to the starlight beam.

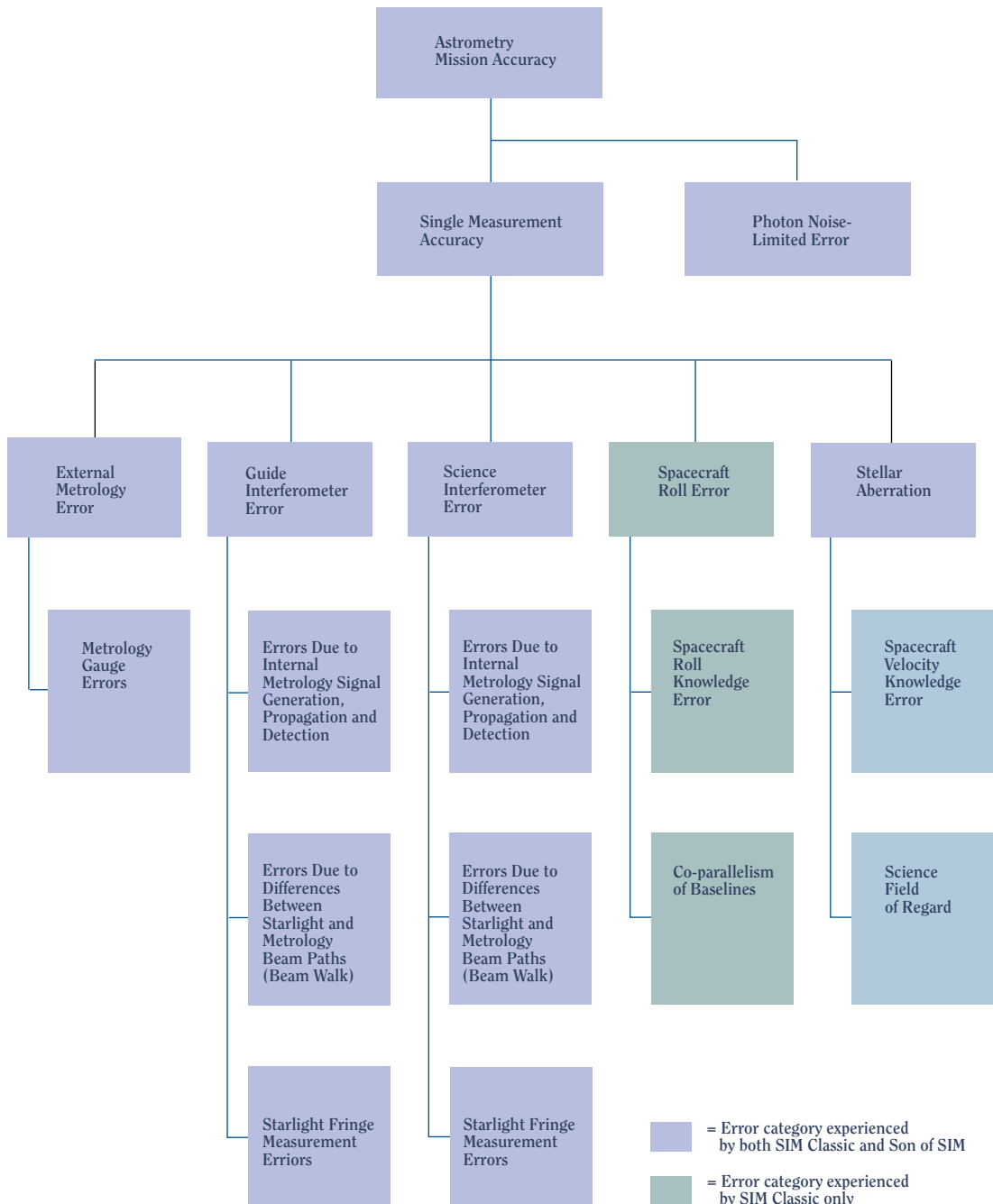
Beam-walk errors occur because of a difference between the metrology and starlight optical paths. As long as this

difference remains constant, the error can be calibrated by the instrument. However, if the metrology-starlight difference varies as the instrument makes its observation, an error in the astrometric measurement will result. This difference can come from a number of sources. Thermal-induced errors described above are one source. Another occurs when the starlight or metrology beam, or both, translate across an aberrated optic. Beam walk across an imperfect mirror can, in turn, occur in a number of ways. This error-budget component captures all these effects. Beam-walk error sources include mispointing of the compressor beam, warping of the structure between the collector pod and combiner pod, shear of the internal metrology beam on the optical fiducial, and variations of the optical footprint as various articulating mirrors articulate to acquire stars. The last error source occurs in the alignment mirror in the Son of SIM design and the siderostat mirror in the SIM Classic design.

Stellar-aberration errors are a relativistic effect due to moving reference frames. The maximum astrometric error σ_θ is approximately given by

$$\sigma_\theta = \frac{2\sigma_v}{c} \sin \frac{\theta_{FOR}}{2}$$

where σ_v is the error in the knowledge of the spacecraft velocity vector, c is the



Nulling
requires
exacting
pathlength,
polariza-
tion, and
intensity
control
levels.

speed of light, and θ_{FOR} is the field of regard (15 degrees). With knowledge better than 4 mm/s, the astrometric error will be less than 0.7 microarcseconds (34 picometers). Other relativistic effects, such as those due to gravitational bending from solar system bodies, have also been studied. With the knowledge of the positions of these bodies, these effects can be kept small by maintaining a small avoidance zone around the major solar system bodies, e.g., the Sun, Jupiter, Saturn, and Earth.

Nulling. SIM will demonstrate the ability to null to a depth of 10^{-4} . This sets several requirements on system-level spacecraft performance, all stemming from the exacting pathlength, polarization, and intensity control levels needed. The most obvious requirement is pathlength control, where an optical path difference of about 1 one-thousandth of a wavelength, or 0.8 nanometer, must be maintained. In addition, a fringe visibility of 0.9998 must be maintained, which calls for equality of intensities from the two interferometer arms to the level of 0.6 percent, and a pointing jitter of under 25 milliarcseconds. The polarizations must also be matched quite accurately, with a differential polarization rotation of under 0.36 degrees, and a differential s-p polarization delay of under 0.72 degree. Thus, a very high degree of symmetry in the two optical trains is necessary.

Spacecraft Design

The spacecraft carries all the instrument components and provides essential operational functions including power, attitude control, propulsion, communication, and thermal control. The spacecraft consists of three major components: the bus module (houses the avionics suite controlling the spacecraft and carries the launch loads into the booster), the payload module (provides the attachment for the precision support structure in both the stowed and deployed configurations), and the precision support structure (provides structural stability for the interferometer).

The bus module has a primary central cylinder housing the propulsion subsystem, radial secondary shear panels supporting modular subsystem compartments, and mechanisms for the antenna and solar array. Flat-panel construction provides a mounting surface for instrumentation and equipment.

The payload module utilizes identical construction techniques and provides the attachment for the precision support structure in the stowed and deployed configuration. The payload module can be thermally and mechanically isolated from the bus module to reduce on-orbit loading, if needed. The stowed flight system design is compatible with the Delta III envelope and current throw-weight estimates.

The precision support structure design employs two deployable “wing” sections to achieve the baseline lengths required for the science goals. Each wing will rotate, from its stowed position, about a fixed hinge axis that incorporates a loose-fitting pin. When deployed, the root section of the wing will engage latch assemblies mounted on the adjacent structure. Mating cup and cone interfaces will assure the alignment of the wing and, once deployed, will provide stability.

The primary avionics suite is based on the NASA Earth Observing System/Advanced X-Ray Astrophysics Facility (EOS/AXAF) line developed at TRW. The central processor has been upgraded to a higher throughput, R3000-based design developed for the U.S. Air Force Space-Based Infrared Flight Demonstration. The command and data handling subsystem processor controls the spacecraft operation, precision support structure deployment, pod movement, thermal control, and interfaces with the instrument processors, all via the Mil Std-1553 interface. The internally redundant processors are continuously powered and remain on throughout the mission life. An X-band communication subsystem comprises an Earth-coverage antenna with a 23-watt traveling wave tube amplifier. The primary data rates at X-band

are 15 megabits/second to the broadcast stations and 150 megabits/second to the playback stations. The electrical power subsystem provides uninterrupted electrical power to the spacecraft and payload, and employs a battery-clamped distribution bus providing DC power to all user loads via a single silicon-cell solar array wing and a 21-ampere hour super nickel-cadmium battery.

The attitude-control subsystem is an EOS-based system providing 15-arc-second, 3σ pointing accuracy per axis. The reaction wheel command and control laws are derived from AXAF vibration-isolated wheels to provide pointing to 14 arcseconds 3σ per axis and slew rates of 0.25 degree per second. To avoid disruption of science data, solar array repointing and momentum unloading is performed during slew maneuvers. The propulsion subsystem is a proven off-the-shelf unit developed for NASA's Total Ozone Mapper.

The thermal control subsystem utilizes flight-proven technologies to satisfy stressing requirements on temperature stability and temperature gradients within the collector pods and the precision support structure. In the precision support structure, a large heater plate is maintained at $20.0 \pm 0.1^\circ \text{C}$. Radiative thermal coupling within a multilayered insulation-wrapped enclosure is rela-

tively weak, so a 0.2°C temperature swing in the heated plates would typically result in a 0.05°C swing in temperature of the precision support structure. Silvered-Teflon multilayer insulation ensures that sunlight illumination will not adversely impact temperature stability. Thermal control of the spacecraft incorporates second-surface mirrored radiators to minimize absorbed solar heating and conventional aluminum heat pipes so that electronics and absorbed solar heating can be transported from the sunlit side of the spacecraft to the shadowed side.

Vibration stability requirements on the precision support structure are currently 18 micro-g below 100 hertz and $0.44\text{ nanometers}/N^{1/2}$ (where N is the number of light bounces) above 100 hertz. Reaction-wheel isolation will employ flight-qualified AXAF isolators, consisting of six viscoelastic damped titanium springs

in a hexapod that supports each wheel individually. The AXAF isolator uses 9-hertz springs with 10-percent damping, and provides near-ideal isolation performance from 10 to 180 hertz. The design can be softened for SIM requirements. Reaction wheels will be operated at a minimum spin rate of 600 rpm to avoid the isolator resonance. Structural damping can be applied throughout the spacecraft using thin viscoelastic layers on panels or struts and damped joints at latch locations, and mechanically advantaged damping layers using graphite standoffs. Another option is to actively enhance the passive isolation, which was demonstrated by a TRW/JPL team on the STB-1 testbed in 1998. The active/passive isolator employed PZT force sensors and voice coil actuators, allowing enhanced isolation from 1 to 100 hertz.